PART 2

LM3-EUTRO

Chapter 3. Model Description

The LM3-Eutro model offers the current "state-of-the-science" in modeling and is capable of providing the type of spatial information lacking in the MICH1 model (Rodgers and Salisbury, 1981a,b) and many other historical Great Lakes frameworks (Di Toro and Connolly, 1980; Thomann and Di Toro, 1975). The model is based on the standard eutrophication kinetics used in the WASP family of models (Thomann and Di Toro, 1975; Ambrose *et al*., 1993) as well as the U.S. Army Corps of Engineers' QUAL models (Cerco and Cole, 1995). Important improvements over earlier Great Lakes models include the high-resolution segmentation and the use of a sophisticated hydrodynamics model (Princeton Ocean Model [POM], Schwab and Beletsky, 1998) to drive the lake's hydrodynamics. Earlier models used tracers such as chloride or temperature to calibrate water movement and account for the transport within a system. These approaches frequently introduced large uncertainties which are, for the most part, avoided with the implementation of the POM.

2.3.1 Transport Scheme for Lake Michigan

Considerable attention had been paid to correctly simulate water column transport in the Lake Michigan Mass Balance Project (LMMBP). The correct implementation of hydrodynamics flow and dispersion and the simulation of concentration gradients had been identified as key elements of water quality analysis for the Lake Michigan System, and they were given particular emphasis throughout the model development.

The computational transport scheme for the LMMBP consisted of three linked submodels in which the output of one submodel was used as input for another submodel. The models consisted of a hydrodynamics model that simulated three-dimensional velocity and temperature fields in the lake, a wave model, and a particle transport model.

The hydrodynamics model was based on the POM which was adapted to Lake Michigan by David Schwab (Schwab and Beletsky, 1998). This model simulated currents, dispersion coefficients, and water temperature over a 5 km grid. The grid was three-dimensional and consisted of 2,318 horizontal cells and 19 vertical layers that resulted in a total of 44,042 water column segments. This 5 km grid was also used in LM3-Eutro. Tributary inflows, the Chicago River outflow, and the Straits of Mackinac were incorporated into POM by David Schwab as part of the hydrodynamics simulation. The POM output consisted of water temperature, horizontal and vertical dispersion, and horizontal and vertical currents for each segment in the water column. This output was used as input for LM3-Eutro. The 1994-1995 POM simulation assumed a constant uniform water temperature of 2°C for the period January 1 to March 31, 1994, while no hydrodynamics data were available after December 21, 1995. In order to obtain hydrodynamics data for the complete 1994-1995 period (used in model calibration and long-term simulations), the first three months of 1994 were replaced with January to March 1995 data (including temperatures), while the corresponding 1994 data was used for the last 10 days in 1995.

The transport model was fairly complex and was incorporated within LM3-Eutro itself. This transport model was based on the ULTIMATE QUICKEST transport scheme, originally developed by Leonard (1991) and subsequently augmented for use with variable grid sizes by Chapman *et al.* (1997). ULTIMATE QUICKEST was also modified by Chapman *et al*. (1997) to incorporate particle settling velocities into the vertical transport calculation, resulting in a more realistic simulation of settling in Lake Michigan. The resulting transport algorithm has been coded in Fortran and applied to the Chesapeake Bay (CE-QUAL-ICM) model (Cerco and Cole, 1994, 1995). A linkage between POM and LM3-Eutro was developed by Chapman *et al.* (1997). The linkage was essentially a mapping of POM cell numbers with ULTIMATE QUICKEST flow face numbers and the relationship between horizontal and vertical components. The LM3-Eutro model calculation performed numerical integration of spatially varying particle concentrations using quadratic interpolation of the concentration to infer its value at flow faces. It also performed analytic integration over space and time to account for changes in the concentration at the cell wall during each time step. Further details of the dimensional derivation of ULTIMATE QUICKEST transport method can be found in Settles *et al*. (2002).

2.3.2 Sediments

The sediments are leaky sinks of nutrients and carbon in Lake Michigan. Phytoplankton and particulate detrital matter containing carbon, nitrogen, phosphorus, and silica settle to the lake bed and are recycled back to the water column *via* resuspension, diagenesis, and diffusion. The ultimate goal of the eutrophication modeling effort was to develop a coupled water column and sediment transport framework. As a short-term approach, the model code was modified to incorporate user-specified sediment fluxes. Although the framework has the flexibility to specify fluxes for any of the state variables, we only used fluxes of the dissolved nutrients (soluble reactive phosphorus [SRP], ammonia [NH_4], dissolved silica [DSi]) and dissolved organic carbon (DOC). These fluxes, in effect, are loads that are evenly distributed over the bottom sediments. These loads were input into the cells of the lowest water column layer, with each cell receiving exactly the same load value. The loads were, thus, independent of time and space. It is well documented that the majority of nutrient mass is recycled within the lake on an annual basis (Meyers and Eadie 1993). Using this knowledge, nutrient sediment fluxes were calculated. These values compared favorably to limited published nutrient fluxes (Quigley and Robbins, 1986; Conley, *et al*., 1988).

2.3.3 Formulation of Eutrophication Equations

Two important features of eutrophication models were the multiple interactions among nutrients, plankton, and sediments and the complexity of the transformation reactions describing the conversions between dissolved and particulate phases. The model simulated two phytoplankton classes, diatoms and “non-diatoms,” a single herbivorous zooplankton class, and several nutrient state variables (Table 2.3.1). In a modeling framework, each interaction was described as a mathematical equation and the challenge was to define a relatively simple expression to approximate complex biochemical processes. Most of the equations formulated and used here were based on the WASP family of models (Thomann and Di Toro, 1975; Ambrose *et al*., 1993) and the CE-QUAL-ICM model (Cerco and Cole, 1995).

Table 2.3.1. Nutrient State Variables

Nutrient	Dissolved Species	Particulate Organic Species
Phosphorus	Soluble reactive, dissolved organic	Labile, refractory
Nitrogen	Ammonia, nitrate, dissolved organic	Labile, refractory
Silica	Biogenic silica	Unavailable silica
Carbon	Dissolved carbon	Labile, refractory

The complete set of mathematical equations used in this model can be found in Appendix 2.3.1. Here we provide a brief explanation of the changes made in formulating the equations describing algal light

dependence, as this was a significant improvement over previous eutrophication modeling approaches.

The general equation for expressing net phytoplankton production is given below.

Net production = gross production - mortality

$$\frac{dp}{dt} = (k_g - k_d) P - k_{gz} Z \quad (2.3.1)$$

where

P = phytoplankton concentration (mass/volume)

t = time

k_g = phytoplankton growth rate (time^{-1})

k_d = phytoplankton mortality rate (time^{-1})

k_{gz} = predation rate (time^{-1})

Z = zooplankton concentration (mass/volume)

The growth rate can be written as:

$$k_g = k_{gmax} f(N) f(T) f(I) \quad (2.3.2)$$

where

k_{gmax} = optimum growth rate (time^{-1})

$f(N)$ = nutrient growth dependency

$f(I)$ = light growth dependency

$f(T)$ = temperature growth dependency

A number of equations had been proposed to describe the effect of light intensity on phytoplankton production. Steele's equation (Steele, 1962) is one of the most commonly used expressions, while a light saturation equation (similar to the Monod equation) is also frequently used (Di Toro *et al*., 1971). We described light dependency in this model according to Steele's equation:

$$f(I) = \frac{I}{I_s} \exp\left[\frac{-I}{I_s} + 1\right] \quad (2.3.3)$$

where

$f(I)$ = light limitation (fraction between 0 and 1)

I = solar light intensity (energy/time/area)

I_s = saturating light intensity (energy/time/area)

The Beer-Lambert equation was used to estimate the light penetration in the water:

$$I_z = I_o \exp(-k_e z) \quad (2.3.4)$$

where

I_z = the light intensity at depth z (energy/time/area)

I_o = the surface light intensity (energy/time/area)

k_e = light extinction coefficient (1/length)

z = depth (length)

Substituting this equation into the previous equation yields:

$$f(I(z)) = \frac{I_0 \exp(-k_e z)}{I_s} \exp\left[\frac{I_0 \exp(-k_e z)}{I_s} + 1\right] \quad (2.3.5)$$

This equation calculates the light limitation at an instantaneous time and at a specific depth. However, for models like ours, light limitation must be estimated in a certain cell (with a given depth range) and over a time period (the time step). Thus, we needed to integrate this equation over time and depth. Di Toro *et al*. (1971) formulated an equation assuming a constant light intensity over the photoperiod. They integrated Steele's equation over a 24-hour period and the total depth of a segment.

$$f(I_a) = \frac{2.718\ fd}{k_e\ \Delta z} [\exp(-\alpha_1) - \exp(-\alpha_0)] \quad (2.3.6)$$

where

$$\alpha_0 = \frac{I_a}{I_s} \exp(-k_e z_1)$$

$$\alpha_1 = \frac{I_a}{I_s} \exp(-k_e z_2)$$

where

fd = the photoperiod

I_a = average light intensity over the photopheriod (energy/time/area)

This approach is still commonly used, although it has been criticized for losing the power to represent midday surface inhibition (Di Toro *et al.*, 1971; Kremer and Nixon, 1978). LM3-Eutro had the luxury of performing variable time averaging from hourly to 12-hour averages and it allowed observation of the differences in time steps. However, if one wanted to estimate the light limitation for less than a day and the average light intensity of that period is known, one can solve Steele's equation as follows (note: it is only integrated over depth, but not over time):

$$f(I_a) = \int_{z1}^{z2} \frac{1}{z} \left(\frac{I_a \exp(-k_e z)}{I_s} \exp\left[\frac{-I_a \exp(-k_e z)}{I_s} + 1 \right] \right) dz \quad (2.3.7)$$

The solution is almost the same as before, without the fraction of daylight in the equation.

$$f(I_a) = \frac{2.718}{k_e \Delta z} [\exp(-\alpha_1) - \exp(-\alpha_0)] \quad (2.3.8)$$

The average light intensity (I_a) can be calculated as follows:

$$I_a = \frac{\int I_0(t)\ dt}{\int dt} \quad (2.3.9)$$

where

I_o = measured incident solar radiation (energy/time/area)

t = time

and can, thus, be approximated by

$$I_a = \frac{1}{n} \sum_{i=1}^{n} I_0(t_n) \quad (2.3.10)$$

where

n = number of discrete time intervals at which I_o is measured

The ability to estimate light limitation on a three-hour basis (the time interval used in LM3-Eutro) rather than an average daily basis allowed a more accurate portrayal of the environment in which phytoplankton grow. The frequency of light measurements in the LMMBP allowed an important model improvement.

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